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Internal Blast in a Compartment-type Vessel

Part 1: Finite Element Modeling Investigation

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Technical Memorandum

DRDC Valcartier TM 2012-222

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Canada

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This work was performed between May and October 2012 under task CSC B32 'Residual strength and stability in a damaged condition'.

Abstract

The objective of this document is to investigate the feasibility of using the LS-DYNA code to perform a finite element analysis to study the structural damage of a typical compartment-type vessel caused by an internal blast. The work is divided into two investigations: one considers the generation and propagation of the blast and the other investigation looks at the material-damage and failure models that could be used to predict the damage on the compartment structure.

The first investigation presents results and lessons learned from four studies. These studies simulated the blast propagation using the arbitrary lagrangian eulerian (ALE) approach in LS-DYNA. This investigation included parametric studies as well. Regardless of the work done, it was not possible to generate a finite element model, fine enough (and yet still manageable) to capture maximum incident pressure and impulse with a domain large enough to include the whole compartment. Alternative methods, such as the raytracer approach, were not part of this work but should be addressed in the future.

The second investigation discusses different issues regarding the use of damage and failure models in LS-DYNA. It is recommended to develop an ad hoc method to predict the damage and failure in large scale model. This method should include a material-damage model, a failure criterion, as well as a study on the mesh. Experimental data should also be used to validate the model.

Résumé

L'objectif de ce document est d'explorer la faisabilité d'utiliser le programme LS-DYNA pour réaliser une analyse par éléments finis permettant d'étudier l'endommagement structurel d'un compartiment typique d'un bateau causé par un effet de souffle interne. Le travail est divisé en deux investigations principales : l'une pour générer et propager l'effet de souffle et l'autre investigation pour explorer les modèles d'endommagement et de rupture qui pourraient être utilisés pour prédire l'endommagement causé par une explosion interne sur la structure du compartiment.

La première partie du travail présente les résultats et les leçons apprises pour quatre études. Ces études ont simulé la propagation de l'explosion en utilisant l'approche arbitraire lagrangienne eulérienne (ALE) dans LS-DYNA. Cette investigation incluait également plusieurs études paramétriques. Malgré tout le travail réalisé, il n'a pas été possible de générer un modèle éléments finis, suffisamment raffiné (tout en restant gérable) pour prédire adéquatement la pression maximale incidente et l'impulsion dans un domaine suffisamment large pour inclure le compartiment au complet. Des méthodes alternatives, telle que l'approche 'raytracer', n'ont pas fait l'objet de ce travail, mais devraient être étudiées dans le futur.

La deuxième partie du travail discute des différentes voies concernant l'utilisation des modèles d'endommagement et de rupture dans LS-DYNA. Il est recommandé de développer une méthode 'ad hoc' pour prédire l'endommagement et la rupture dans un modèle à grande échelle. Cette méthode devrait inclure un modèle d'endommagement, un critère de rupture, ainsi qu'une étude de maillage. Des données expérimentales devraient aussi être utilisées pour valider le modèle.

Executive summary

Internal Blast in a Compartment-type Vessel: Part 1: Finite Element Modeling Investigation

Geneviève Toussaint; Claude Fortier; Stéphane Dumas; DRDC Valcartier TM 2012-222; Defence R&D Canada – Valcartier; November 2012.

Introduction or background: DRDC Atlantic requested DRDC Valcartier to evaluate the damage on ship structures such as bulkheads and decks produced by a charge detonated in a compartment-type vessel by conducting parametric simulations (analytical or using finite element) on charge size, location, etc. Blast propagation to neighbouring compartments was also of interest. After discussions on the possible solutions and considering the short term deadline, it was decided to investigate the feasibility of using LS-DYNA to perform the finite element structural analysis to study the structural damage of a typical compartment-type vessel. The work was divided into two main activities: first, various blast loading and propagation methods usable in LS-DYNA were investigated; second, a discussion on the material damage and failure models that could be used to predict the damage on the compartment structure is presented.

Results and significance: This work has demonstrated the limitations of actual CFD/FE models to simulate an accurate internal blast, including shock reflections and quasi static pressure, in a large structure and the need to address this gap by using alternative methods. It also demonstrated the need to develop a method to predict the damage and failure caused to the compartment structure.

Future plans: Current blast propagation methods are probably adequate for modeling the quasi-static phase and effects on neighbouring compartments as long as the panel rupture is modeled realistically. However, on a more long term basis, the development and validation of a raytracer and its coupling with LS-DYNA will be addressed for modeling the shock loading in the first compartment.

Sommaire

Internal Blast in a Compartment-type Vessel: Part 1: Finite Element Modeling Investigation

Geneviève Toussaint; Claude Fortier; Stéphane Dumas ; DRDC Valcartier TM 2012-222 ; R & D pour la défense Canada – Valcartier; novembre 2012.

Introduction ou contexte : DRDC Atlantique a demandé à DRDC Valcartier d'évaluer le dommage causé à des structures navales telles que des cloisons et ponts produit~~es~~ par une explosion dans un compartiment de bateau typique en effectuant des simulations paramétriques (analytiques ou par éléments finis) sur la dimension de la charge, sa localisation, etc. La propagation des effets de souffle aux compartiments adjacents présentait aussi un intérêt. Après discussion sur les solutions possibles et considérant le court délai pour effectuer le travail, il a été décidé d'investiguer la faisabilité d'utiliser LS-DYNA pour réaliser des analyses par éléments finis visant à étudier l'endommagement structurel d'un compartiment typique de bateau. Le travail a été divisé en deux activités principales : en premier, différentes méthodes disponibles dans LS-DYNA pour générer et propager le souffle d'explosion ont été étudiées; en deuxième, une discussion sur les modèles d'endommagement matériel et de rupture qui pourraient être utilisés pour prédire l'endommagement et la rupture des structures est présentée.

Résultats et Importance: Ce travail a démontré les limitations des modèles EF actuels pour simuler adéquatement le souffle d'explosion, incluant le choc et ses réflexions, à l'intérieur d'une large structure et le besoin de remédier à cette lacune en utilisant des méthodes alternatives. Ce travail a aussi démontré le besoin de développer une méthode pour prédire l'endommagement et la rupture causée à la structure du compartiment.

Perspectives : Les méthodes actuelles semblent adéquates pour modéliser la phase de pression quasi-statique et ses effets sur les compartiments voisins, en autant qu'on dispose de modèles de rupture de panneaux réalistes. Cependant, à long terme, le développement et la validation d'un 'raytracer' et son couplage avec LS-DYNA seront étudiés pour modéliser le choc dans le compartiment initial.

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1 Introduction

DRDC Atlantic requested support from DRDC Valcartier concerning the Canadian Surface Combatant (CSC) project. The objective of the short-term[1] task to which this paper contributes was to compare and quantify the strength and stability implications of damage to a CSC-type concept ship, with the idea of highlighting potential design problems. After discussion between DRDC Valcartier and DRDC Atlantic, internal blast was identified as the driving threat to be considered.

It was decided to conduct parametric simulations (analytical or using finite element) on charge size, location, etc., to evaluate the damage on structures such as bulkheads and decks. The results obtained could be used to produce or modify requirements for the System Requirements Document (SRD) [Pegg (2012)]. After discussions on the possible solutions, it was decided to investigate the feasibility of using LS-DYNA to perform finite element structural analyses studying the structural damage of a typical compartment. To do that, the work was divided in two main activities: the first one studied various methods used to generate and propagate the blast (including reflections if necessary) and the other one discussed the material damage and failure models in LS-DYNA that could be used to predict the structural behaviour of the compartment walls, ceiling and floor; which included damage/erosion on the elements and possible venting to other compartments.

This work was performed between May and October 2012 under task CSC B32 'Residual strength and stability in a damaged condition'.

[1] To be completed in 2012

2 Blast modeling

The first sub-section presents several methods that are used typically in the DRDC Valcartier Weapons Effects and Protection (WEP) section to simulate internal and external blasts. The second sub-section presents various finite element modeling studies that were performed to simulate an internal blast.

2.1 Loading methods

Without even talking about blast propagation between compartments, simulating the effect of an internal blast in a single compartment using the finite element method is challenging because it implies:

1) modeling multiple shock reflections in the initial compartment with sufficient resolution to represent realistically a very thin shock surface.

2) modeling an extensive number of structural elements over a compartment having dimensions reaching several meters.

Actually, DRDC Valcartier uses several methods to model land mine and air blast: CONWEP model [Hyde (1988), Randers-Pehrson and Bannister (1997)]; Westine model [Westine (1985)]; Pressure-based mine loading model [Toussaint and Bouamoul (2010)]; Chinook code [Martec (2005)]; arbitrary lagrangian eulerian (ALE) and smoothed particle hydrodynamic methods (SPH) [Toussaint and Bouamoul (2010), LS-DYNA Theory Manual (2006)]. Since Westine and the in-house pressure models are typically used to simulate land mine blast, they are not suitable for internal blast. Also, according to [Toussaint and Bouamoul (2010)], the ALE method predicted better the expansion of air blast than SPH, so SPH was not considered. Therefore, to simulate internal blast two methods were considered in this work: CONWEP and ALE. However, two other approaches were shortly described: Chinook and raytracer.

2.1.1 CONWEP

According to Schwer (2010-A), Kingery and Bulmash (1984) '*parameterized an extensive collection of air blast experimental data using two fundamental air blast principals: TNT Equivalence of difference explosives and Cube Root Scaling of range, impulse, and time with explosive weight*'. The Friedlander equation combined with the parameterization of these experimental data, are the founding principles of CONWEP. The air blast portion of CONWEP was implemented in LS-DYNA by Rahnders-Pehrson and Bannister (1997) as an air blast function called **load_blast* that treats free-air burst, surface burst and the more recent version **load_blast_enhanced* (LBE), can also treats moving free air burst and height of burst type problem [LS-DYNA Keyword's User's Manual (2012)]. One limitation of the LBE technique is that it can apply a pressure load on segments but the incident and reflected waves cannot interact. For example, LBE cannot account for reflections produce in the interior corner of a room.

In CONWEP, the range of applicability for the positive phase duration of a spherical free air explosion is 2.7 to 750 charge radii. That's why in simulation runs the minimum range of applicability for CONWEP is usually considered to be three times the charge radii. However, Schwer (2010-B) showed that this number was not strictly correct (see Annex A). Schwer (2010) presented a comparison between the pressure and impulse of a TNT free air burst of 4.5 kg and 454.5 kg given by Swizdak (1975) and that predicted by CONWEP. The comparisons between them showed that the maximum incident pressures agreed quite well; however, CONWEP overpredicted the impulses at close range. Therefore, a new range of applicability of 7.57 should be used in this work to compare the impulse data with CONWEP's predictions (see Annex A) for a 100 kg spherical charge of TNT.

Therefore, in this work, the **load_blast* card in LS-DYNA should not be used to load elements at a distance closer than 1.852 m for a 100 kg TNT charge. As well, when we compare numerical simulation predictions with CONWEP's impulse, this should be done only for distances further than 1.852 m but we can compare the maximum incident pressure from CONWEP from 0.734 m (charge radii of 3).

The main advantage of CONWEP is that it is both fast (no CFD required) and reliable when used within the calibration range. The main disadvantage is that it is limited to simple interactions (no shock reflections).

2.1.2 ALE

The ALE formulation allows modeling the blast as a fluid. One advantage of this formulation is that it can model the interaction of incident and reflected waves. However, what limits the use of this model for large scale is that each element must be very small to capture the shock pressure. For example, Dong et al. (2009) modeled air with element mesh size smaller than 1 mm. Slavik (2009) showed that an ALE mesh with element size fixed to 4 mm seemed appropriate. Toussaint and Bouamoul (2010) showed that air element size fixed to 40 mm seemed adequate to reproduce the experimental velocity profile of a structure resulting from an air blast. In the actual work, the element size for the ALE domain is one of the most difficult parameters to overcome. This is due to the size of the compartment (the ALE air model is defined by a box of dimensions: 8.1m x 4.6m x 11.8 m). Because the compartment is not symmetric, a quarter or half model could not be used.

2.1.3 Chinook

Chinook[2][3] is a CFD code designed specifically for modeling fast blast loadings (shocks), accounting for phenomena such as focusing, channelling, clearing and sheltering effects. It models blast pressure loads on different platforms such as vehicles and personnel. It also models multiple materials (explosives, solids, water, gases, and mixtures) and it models blast and ejecta resulting from land mine explosion. This code seems well suited for internal blast modeling, when close threat modeling is required or for a complex scenario modeling and was validated with experimental data. Martec has previously used Chinook for CPF vulnerability to IEDs

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[2] Chinook Software was developed by Martec Limited in partnership with DRDC.
[3] www.martec.com

[Martec (2005)]. Chinook is seen as more efficient than LS-DYNA's internal CFD-like module (ALE, SPH, CONWEP) for modeling shock effects and may be coupled with LS-DYNA for modeling fluid-structure interactions. The 2D code seems to work with reasonable run times; however, the execution time for the 3D code is very long. Therefore, we may encounter the same limitations as in the 3D ALE model concerning the small cell size required to model accurate maximum incident pressure.

Since coupling with Chinook has not been fully experimented yet by DRDC Valcartier and due to the timeline given to realise the work, Chinook was only explored. In order to get started using Chinook and for future needs, a training session was organised in September 2012. This included exploration of the fluid-structure coupling.

2.1.4 Raytracer

The raytracer is a method using virtual sources to assess the pressure at a location (i.e. a gage). The version presently experimented assumes a rectangular room with perpendicular walls. The algorithm can support any number of explosives and gages. The resultant pressures recorded is the combined pressure histories from the incident shockwaves and reflections from the walls and from all explosives (several at a time may be modeled). Another advantage is that it avoids the modeling of air cells so that loading the walls is much faster than using ALE or Chinook. This method is still under development and coupling with LS-DYNA has to been done yet. However, it is a promising tool and should allow efficient and reasonably accurate modeling of an internal blast in a compartment-type vessel.

2.2 Finite Element Modeling

This sub-section presents four studies that were realised to investigate the feasibility of using LS-DYNA to simulate accurately the propagation of an internal blast considering the size of a typical compartment-type vessel. The first study presents the simulation of a blast propagating in a simple multi-material ALE FE model of a rectangular box meshed with elements of 200 mm. In the second study, this FE model was refined and three new FE models were generated with element sizes of 100 mm, 75 mm and 50 mm. The third study presents the combination of the **load_blast_enhanced* (LBE) keyword and the multi-material ALE approach to generate the blast. The fourth study presents the propagation of the blast in a spherical domain. Finally, alternative approaches to generate and propagate the blast are presented.

Note that in principle, cells should be taken much smaller than those above to capture shock features. However, higher resolutions would be almost unmanageable, especially if extended to several compartments. It is then of interest to check if convincing loadings could be modeled with the above resolutions. Given the relatively slow panel response times compared to shock durations, impulse may be more important than (very short duration) peak pressures.

The compartment-type vessel, as shown in Figure 1, is made of shell elements and beam sections. Notice that the compartment is not symmetric. Notice also that, the final objective is to be able to use the finite element model to conduct parametric simulations on charge size, location (ex.: top corner, bottom corner, mid-wall...), etc., to evaluate the damage on structures such as bulkheads and decks. Therefore, the approach chosen should allow the positioning of the charges easily

everywhere in the compartment without the need to regenerate the FE model for each possible scenario.

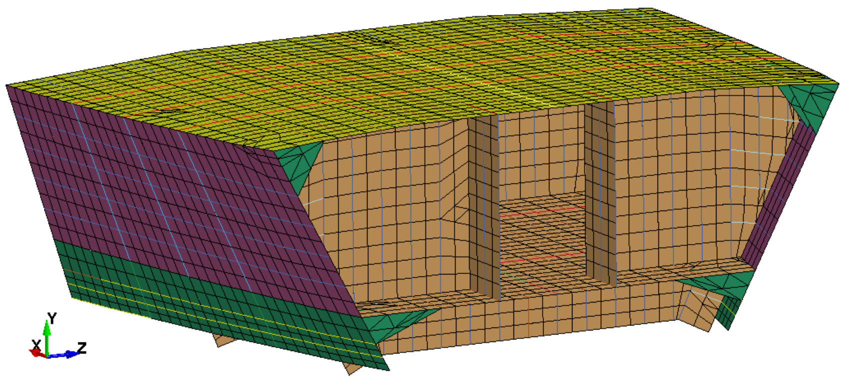

Figure 1: Compartment-type vessel

2.2.1 First study

The first FE model created in FEMAP[4] was a rectangular box with dimensions of 5.8 m x 9.6 m x 13.2 m. A total of 91,872 elements were generated with element size of 200 mm. A sphere representing a mass of 100 kg TNT was defined using the **Initial_volume_fraction* geometry card and positioned in the middle of the box. The mesh was uniform because the FE model had to be valid for any charge locations in the box.

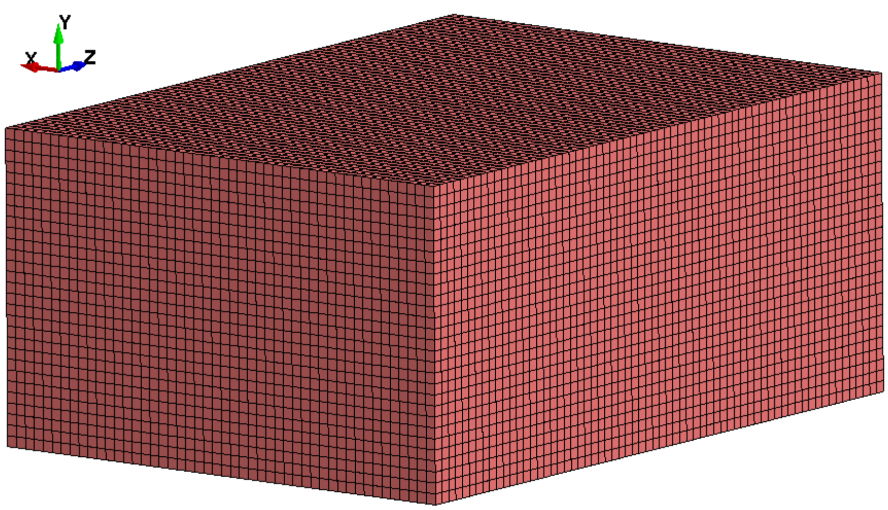

Figure 2: ALE rectangular mesh[5] with element size of 200 mm

[4] FEMAP was used to generate all the FE models of this work.
[5] The units for all the FE models and results in this work are: g, mm, ms, MPa, N.

A pressure of 101 kPa was applied on the outside boundaries of the box and inside the compartment. A **boundary_non_reflecting* (BNR) card was specified to avoid reflection waves to re-enter in the model. The air was modeled with the **mat_null* material model using a linear polynomial equation of state. Properties are provided in Table 1 and Table 2. The explosive was modeled using **mat_high_explosive_burn* material combined with the Jones Wilkins Lee (JWL) equation of state. Properties are provided in Table 3 and Table 4.

*Table 1: *Mat null material parameters [Toussaint and Bouamoul (2010)]*

	Air
Density (ρ), g/mm^3	1.293×10^{-6}
Pressure cutoff (P_C), MPa	0

*Table 2: *EOS linear polynomial [Toussaint and Bouamoul (2010)]*

	Air
Polynomial equation coefficient C0, C1, C2, C3 and C6	0.0
Polynomial equation coefficient C4 and C5	0.4
Initial internal energy (E0), MPa	0.25
Initial relative volume (V0)	1.0

Table 3: Explosive properties [Dobratz and Crawford (1985)]

	TNT
Density (ρ), g/mm^3	1.630×10^{-3}
Detonation velocity (D), mm/ms	6930
Chapman-Jouget pressure (P_{CJ}), MPa	21×10^3

*Table 4: *EOS JWL [Dobratz and Crawford (1985)]*

	JWL
A, MPa	3.712×10^5
B, MPa	3.231×10^3
R1	4.15
R2	0.95
Omega (ω)	0.30
Internal energy density (E_0), MPa – mm^3/mm^3	7.0×10^3
Initial relative volume (V_0)	1.0

The finite element structural code LS-DYNA was used to simulate the blast wave propagation in the box.

For the first run, the center of detonation was located in the middle of one element (y axis) as shown in Figure 3. Also, one effect of having a coarse mesh is that the explosive is represented by a tetrahedron instead of a sphere made of many cells.

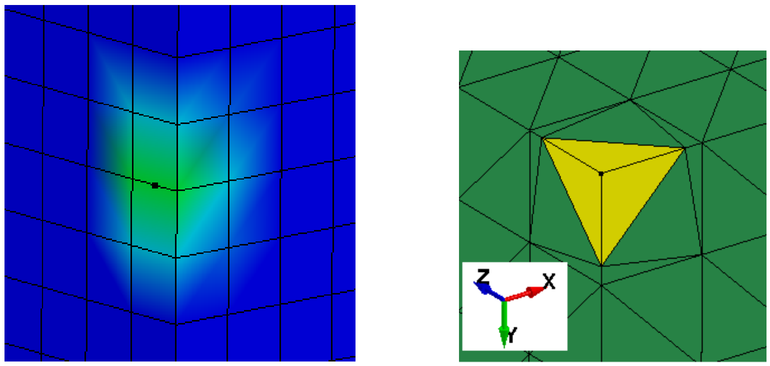

Figure 3: a) Location of the center of detonation b) Explosive representation in ALE model

When analysing the results of the simulation, we observed that the results obtained on the axis (y) were different than the ones obtained on the x and z axis (at the same range). To reduce this effect, the center of the explosion and the detonation point were moved from the initial location on the y axis to the closest node location, as shown in red, in Figure 4. Even by doing so, at 0° on the xy, yz and xz plane, the pressures predicted were slightly different at the same range from the center of detonation. This could be explained by the fact that even if a BNR card was used, there were still reflections at the boundaries. This could be reduced by pushing the boundaries far enough from the center of detonation but in this case, it was not possible due to the size of the problem.

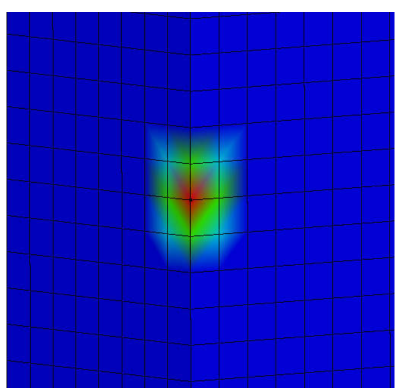

Figure 4: New location of the center of detonation

Giving the range of applicability from Swizdak (1975), for a 100 kg charge, the distance in charge radii should be set 7.57 (see Annex A) which corresponds to 1.852 m for the comparison

between the impulse predictions from CONWEP and numerical results. The maximum incident pressure and impulse obtained at 1.5 m, 2 m and 3 m are given in Table 5 and Table 6.

Table 5: Maximum incident pressure obtained for a rectangular mesh with element size of 200 mm compared to the CONWEP predictions

Distance (m)	**Mesh 200 mm**	**CONWEP**
	Pressure (MPa)	**Pressure (MPa)**
1.5	14.148	8.059
2.0	5.07413	5.064
3.0	4.626053	2.369

Table 6: Impulse obtained for a rectangular mesh with element size of 200 mm compared to the CONWEP predictions

Distance (m)	**Mesh 200mm**	**CONWEP**
	Impulse (MPa•ms)	**Impulse (MPa•ms)**
1.5	1.27703	
2.0	0.836873	0.6352
3.0	1.2140875	0.7585

Note that when the location of the pressure gauge fell between two elements, the mean of the pressure of both elements was taken.

This table highlights some limitations of this model; the FE model overpredicts the maximum incident pressure and impulse compared to CONWEP. In order to see if refining the mesh will increase the maximum incident pressure and total impulse, a convergence study is required and will be presented in the next section.

Lessons were learned from this study:

- The center of detonation must be coincident with a node (not in the middle of an element).

- Even if a non-reflective condition is given on the outside boundaries, the boundaries should be as far as possible.

- Elements must be smaller than 200 mm.

- The explosive should be defined with many elements (depending on the charge radius).

2.2.2 Second study

In the previous sub-section, a 3D rectangular mesh was generated with a mesh size of 200 mm. It was demonstrated that elements with a mesh size of 200 mm did not capture accurately the maximum incident pressure and impulse at different locations from the center of detonation. Also, it was showed that the size of the mesh cells must be sufficiently small to allow the propagation of a nice spherical blast.

In this study, a finite element model of dimensions 8.1m x 4.6m x 11.8 m was modeled with hexahedron ALE elements with mesh sizes of 100 mm (439,668 elements), 75 mm (1,034,316 elements) and 50 mm (3, 517,344 elements). Elements were not smaller than 50 mm because it generated too many elements that couldn't be handled by FEMAP on my workstation[6]. A boundary non-reflecting card was specified to limit the reflection at the boundaries. The meshes are shown in the following figures.

Figure 5: Rectangular mesh-100 mm

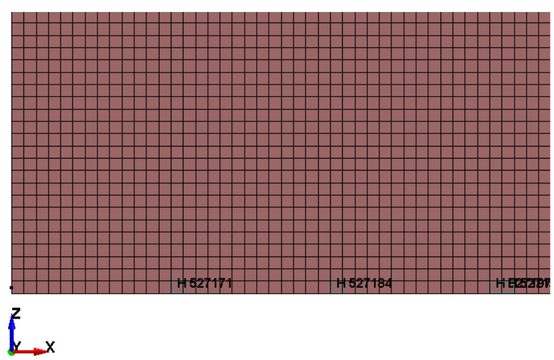

Figure 6: Rectangular mesh-75 mm

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[6] We tried modeling the rectangular mesh with elements size of 40 mm without success.

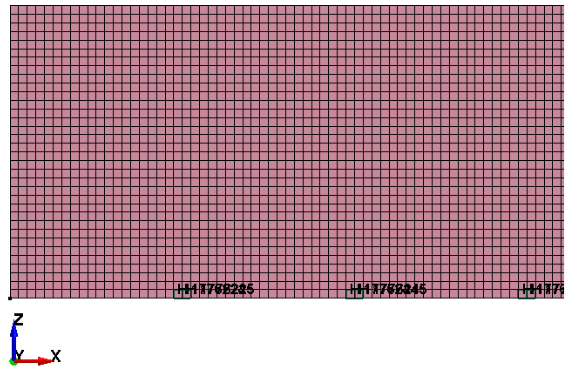

Figure 7: Rectangular mesh-50 mm

The finite element structural code LS-DYNA v5.1.1 using multiple processors was used to simulate the blast wave propagation of a 100 kg TNT charge located in the middle of the box. Several problems were encountered. For example, the timestep of the d3plot recorded needed to be decreased in order to capture the peak pressure that fell between two measurements in the simulation. The center of detonation had to be moved to fit with a node location (see Figure 5 and Figure 6) such as in the previous study. Also, there were some reflections in the model even if a BNR card was used and boundaries could not be moved further. Figure 8 shows an example of an air blast propagation.

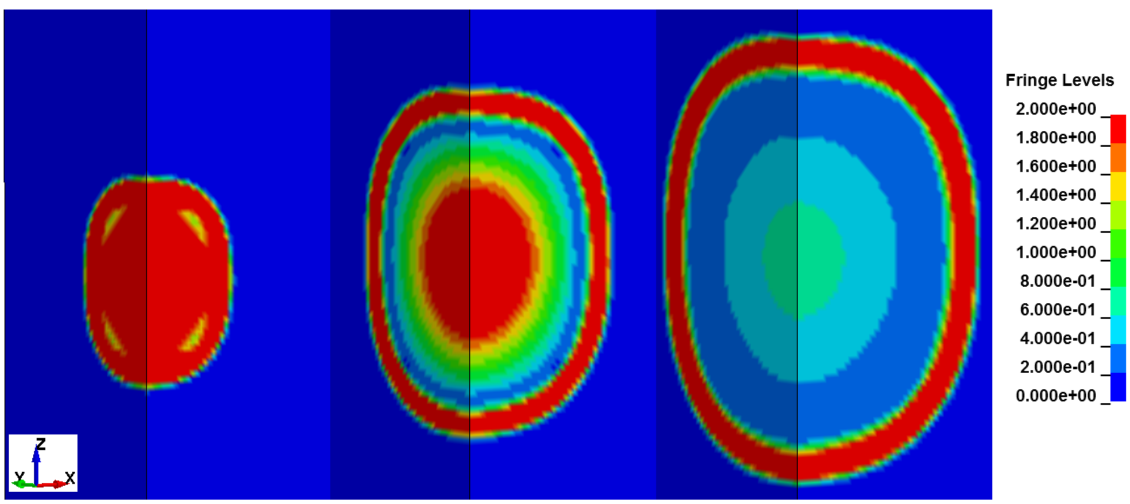

Figure 8: Example of blast propagation in the FE model (MPa)

A comparison of the maximum incident pressure and total impulse taken at 1.5 m, 2 m and 3 m obtained for the different meshes and the CONWEP predictions are given in Table 7 and Table 8. Annex B presents an example of the curves obtained.

Table 7: Maximum incident pressure obtained for a rectangular mesh with element size of 100 mm, 75 mm and 50 mm compared to CONWEP results

Distance (m)	Peak Pressure (MPa)			CONWEP (MPa)
	Mesh 100 mm	Mesh 75 mm	Mesh 50 mm	
1.5	1.878	2.972	4.357	8.059
2.0	1.861	2.325	2.957	5.064
3.0	1.195	1.446	1.712	2.369

Table 8: Impulse obtained for a rectangular mesh with element size of 100 mm, 75 mm and 50 mm compared to CONWEP results

Distance (m)	Impulse (MPa•ms)			CONWEP (MPa•ms)
	Mesh 100 mm	Mesh 75 mm	Mesh 50 mm	
1.5	0.2997	0.3573	0.4260	0.6723
2.0	0.3886	0.4372	0.4926	0.6352
3.0	0.6436	0.6687	0.6752	0.7585

Note that when the location of the pressure fell between two elements, the mean of the pressure of both elements was taken.

Table 7 shows that peak pressure increases when refining the mesh and decreases when increasing the distance. It can also be seen that a mesh of 50 mm is not sufficient to capture adequately the maximum incident pressure predicted by CONWEP. According to Mahmadi et al. (2002) and Alia and Souli (2006), it is possible to match accurately the peak pressure when the mesh is fine enough. In this case, it would probably require running the problem with element in the order of 1 to 10 mm which seems almost impossible for a ship size problem.

Table 8 shows that total impulse increases when refining the mesh and increases also when the distance increases. Results obtained are still not sufficiently close to the CONWEP predictions. Moreover, CONWEP predicts a reduction of the total impulse at 2 m that is not captured by any of the three models.

To reduce the multi-material ALE domain (i.e. reduce the number of elements), another approach has to be chosen. This method is presented in the next section and consists in coupling the multi-material ALE model with a **load_blast_enhanced* keyword in LS-DYNA as presented in Schwer (2010-B).

Some lessons were learned from this study:

- Elements smaller than 50 mm are required to capture peak pressure and total impulse produced by a 100 kg TNT detonation at close range (< to 3 m).

- There is a need to increase the frequency of d3plot data at a minimum of 0.01ms to capture the highest pressure.

- The pressure in the elements along each principal axes and at 45° should always be compared.

2.2.3 Third study

The previous sub-section showed that the element mesh must be smaller than 50 mm to capture the maximum incident pressure and impulse data. The objective of this third approach is to find a way to reduce the number of ALE elements in the model and consequently, to increase the mesh size to get maximum incident pressure and total impulse closer to the CONWEP predictions. One solution to limit the number of elements in the model, and at the same time minimize the computational cost, is to combine the LBE technique with an ALE model. This technique is well explained in Schwer (2010-B). The load produced by LBE is applied to the elements at the outer surface of the eulerian mesh. The interior wave reflections are then treated by the multi-material ALE solver. With this method, there is no need to model all the air elements from the charge to the target, only a smaller air box is required around each wall/ceiling.

In the multi-material ALE approach coupled to the **load_blast_enhanced* (LBE-ALE) keyword in LS-DYNA, the explosive is not modeled physically; instead, a load pressure is applied to the air segments forming the boundary facing the location of the charge. Figure 9 shows an example. Instead of modeling the whole domain with multi-material ALE (like in section 2.2), only a portion of the model is meshed (pink zone) and the pressure is applied on the first row of elements forming the frontier. One advantage of using this technique is to reduce the domain (number of elements) to be modeled and another advantage is that reflections can still occur in the multi-material ALE domain. However, outside the multi-material ALE domain, reflections are not accounted for. Also, in this work, LBE should not be applied on a frontier closer to 3 charge radii (for maximum incident pressure) and preferably 8 charge radii (for impulse) which means that near field blast and multiple internal blasts cannot be modeled with this technique.

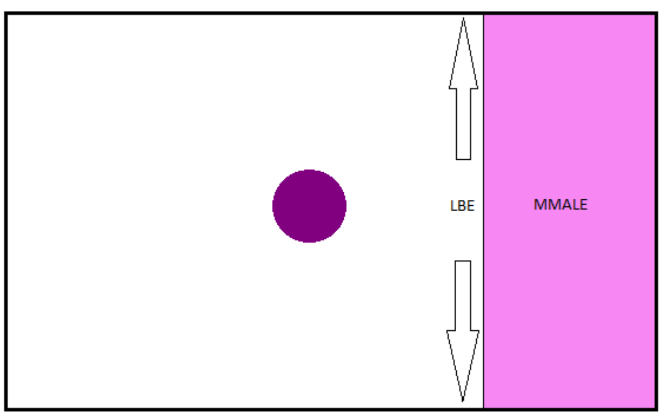

Figure 9: LBE-ALE example

In this study, since only a portion of the 3D rectangular box presented previously was used, the mesh could be refined. Figure 10 shows the LBE frontier (in purple) for three meshes size of 100

mm, 50 mm and 10 mm. For each mesh, the ALE model (including the first layer of elements where the LBE is applied) was moved at the different locations (1.5 m, 2 m and 3 m from the center of detonation) to get maximum incident pressure and impulse at each of these locations.

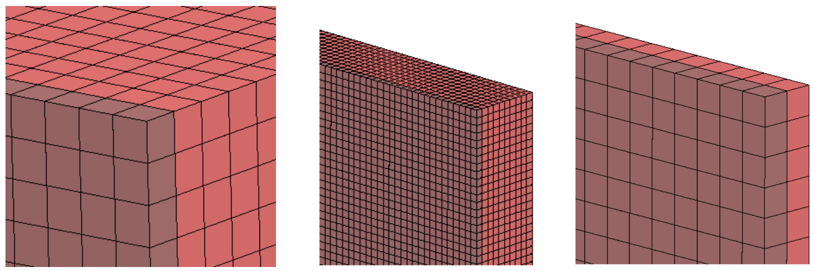

Figure 10: ALE mesh where the load is applied (100 mm – 50 mm – 10 mm)

The finite element structural code LS-DYNA v5.1.1 was run on a single processor to simulate the blast wave propagation of a 100 kg TNT charge located in the middle of the box. Note that the loading generated on these segments (layer) did not depend on the number of elements in the back. Table 9 and Table 10 show the results of the peak pressure and impulse measured at 1.5 m, 2 m and 3 m for each LBE-ALE mesh (measurements taken perpendicularly to the charge). The results obtained are compared to the CONWEP predictions.

Table 9: Maximum incident pressure obtained for the LBE-ALE model with mesh sizes of 100 mm, 50 mm and 10 mm compared to the CONWEP predictions

Distance (m)	**Peak Pressure (MPa)**			**CONWEP (MPa)**
	Mesh 100 mm	**Mesh 50 mm**	**Mesh 10 mm**	
1.5	7.648	7.617	6.823	8.059
2.0	4.535	4.491	4.322	5.064
3.0	2.328	2.326	2.175	2.369

Table 10: Impulse obtained for the LBE-ALE model with mesh sizes of 100 mm, 50 mm and 10 mm compared to the CONWEP predictions

Distance (m)	**Impulse (MPa•ms)**			**CONWEP (MPa•ms)**
	Mesh 100 mm	**Mesh 50 mm**	**Mesh 10 mm**	
1.5	0.6857	0.6714	0.6289	0.6723
2.0	0.6095	0.6027	0.5772	0.6352
3.0	0.7525	0.7440	0.7293	0.7585

Table 9 shows that the peak pressure decreases when refining the mesh. Table 10 shows that the impulse decreases when refining the mesh. We expected the opposite behaviour.

For the same element size, the FE model results are much closer to the CONWEP predictions when using the LBE-ALE model than using only a multi-material ALE model.

Both tables showed that the best correlation between the FE model and the CONWEP predictions is for a mesh with element size of 100 mm. Therefore, with element size of 100 mm, the LBE-ALE captured adequately the initial loading. This approach could be used to model the effect of a direct loading only (no reflections) on the compartment walls. In this work, it will not be useful as we want to model the effect of multiple reflections on the compartment structure.

2.2.4 Fourth study

In the previous studies, a rectangular mesh domain was used to propagate the blast. The main disadvantage of a rectangular grid is that even at the same distance from the center of detonation, the pressure predicted varied in all directions. Schwer et al. (2008) compared the maximum impulse in the xy plane at 0°, 22.5°, 45°, 67.5° and 90° and showed large variations between the results when using a rectangular mesh compared to a spherical one. It is possible to reduce this directional dependence by refining the mesh or to eliminate the problem by using a spherical coordinate system.

In this section we generated a spherical domain. One advantage of using a spherical domain is that it requires a lot less element than using a rectangular domain so the elements near the detonation can be smaller. Another advantage is that there is no directional dependence of the mesh. However, once the blast has reached the structure the wave reflected will not be in the direction of the spherical mesh and therefore the reflections might not be accurate[7]. Also, using this mesh, only a centered detonation in the compartment is possible, because an off centered detonation (in the corner for example) would require moving the mesh in the corner and would require generating more elements to the domain to enclose all the compartment structure. This would add too many elements to the mesh.

The finite element model of the explosive modeled was generated using a small cube box in the center of a sphere with a radius of 245 mm. For generating the FE model of the air, the elements from the surface of the explosive were extruded using 300 elements on a 4.755 m radius with a thickness bias of 5. Three element sizes of 10 mm, 5 mm and 4 mm for the initial cubic box were generated. The initial mesh of 4 mm had a higher growth factor than the initial mesh of 5mm in order to keep the number of elements acceptable (5 mm: 3,222,400 elements and 4 mm: 3,290,000 elements).

The central 5 mm mesh is shown in Figure 11. Due to the number of elements generated, the radius of the domain had to be set to a maximum of 5 m which allowed to include only the nearest walls of the compartment, not the whole compartment. A boundary non-reflecting card was specified to limit the reflection at the boundaries.

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[7] It might be possible to get around the problem by using an adaptative mesh, but it was not tested in this work.

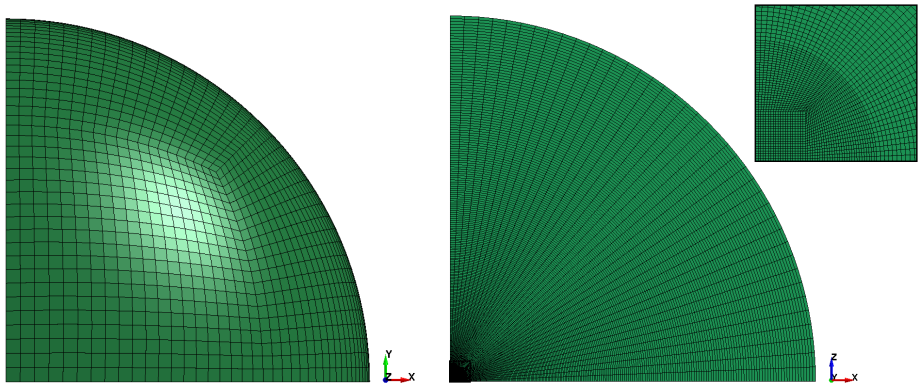

Figure 11: Initial mesh: 5 mm

The finite element structural code LS-DYNA v5.1.1 was used to simulate the blast wave propagation of a 100 kg TNT charge located in the middle of the sphere. Many FE analyses were performed to study the effect of parameters such as: element size, growth factor, equation of state for the explosive and to study the influence of using method 2 versus method 3 in the **control_ale* card. All the results obtained from these FE analyses are not presented in this work, only the final results for the mesh size of 5 mm using the JWL equation of state and method 2 in the **control_ale* card are presented. These results are given in Table 11 and Table 12.

Table 11: Maximum incident pressure obtained for a spherical model with mesh sizes of 5 mm compared to CONWEP predictions

Distance (m)	**Mesh 5 mm**	**CONWEP**
	Pressure (MPa)	**Pressure (MPa)**
1.5	5.9797	8.059
2.0	4.1897	5.064
3.0	2.0650	2.369

Table 12: Impulse obtained for a spherical model with mesh sizes of 5 mm compared to CONWEP predictions

Distance (m)	**Mesh 5mm**	**CONWEP**
	Impulse (MPa•ms)	**Impulse (MPa•ms)**
1.5	0.6829	0.6723
2.0	0.6864	0.6352
3.0	0.6246	0.7585

Table 11 shows that maximum incident pressures predicted by the spherical multi-material ALE mesh are 26% lower at 1.5 m, 17% lower at 2 m and 13% at 3 m than the CONWEP predictions. However, when these predictions are compared to the predictions of the multi-material ALE

rectangular mesh with the smallest mesh (Table 7), the spherical mesh provides a better agreement with the CONWEP predictions.

Table 12 shows that impulse predicted by the spherical multi-material ALE mesh (after 1.852 m) are 8% higher at 2 m and 18% lower at 3 m than the CONWEP predictions.

One advantage of the spherical mesh is that the maximum incident pressure and impulse predicted by the spherical domain compared to the CONWEP predictions were closer than the ones obtained with a rectangular domain having approximately the same number of elements. Another advantage of the spherical mesh over the rectangular mesh was that there is no directional dependence of the mesh. However; in a spherical mesh, the loading resulting from multiple reflections would not be accurate.

2.2.5 Alternative approaches

The approaches taken to simulate the blast wave propagation in a compartment type vessel using LS-DYNA were not very successful. Other methods could have been tested. However, due to the short time given to realise this work, it was not possible to investigate all of them. Here are a few suggestions that could be tested in the future:

1. Divide the rectangular mesh into 10 parts, each part having its own input file. The element size in each part could be around 25 mm. In the main file, use the **include* card to include all the parts in one model and use the **nodes_merge_set* option in LS-DYNA to join all the nodes between the parts. Instead of being limited by FEMAP, it is the execution time that will be limited by the number of elements.

2. One possible solution to reduce the number of elements in the model is demonstrated in Aquelet and Souli (2008). The technique is to map axi-symmetric blast wave propagation from 2D ALE mesh to 3D ALE mesh and then, to run the ALE 3D problem with LS-DYNA code. Zakrisson et al. (2011) used that technique to simulate a near-field 0.75 kg charge weight detonated in free air. A convergence study was performed to validate the choice of the 2D and 3D mesh. They ended using element side length of 0.5 mm for the 2D mesh mapped to 4 mm element length (using a biaised distribution) for the 3D mesh. Mapping from 2D to 3D ALE mesh appears feasible in the actual work; it would allow modeling a very fine mesh in two dimensions before the mapping to 3D. Also, it would require two convergence studies instead of one. Since the ceiling and floor are located approximately 2 m from the center, the model would be useful for a centered detonation between ceiling and floor only and not too close from the walls. Of course, the remaining parts of the domain would have to be modeled with 3D elements. This would also solve only part of the problem as subsequent reflections would not be accurate.

3. Map 2D mesh to a 3D mesh using Chinook. The same limitations as stated in the previous point form would apply. A full 3D Chinook solution, would very likely require resolutions too high to be manageable on such a large scale (i.e. same problems as with ALE). This was discussed with Martec specialists that concluded that modeling multiple reflections until the onset of quasi-static pressure was not realistic.

4. Finally, the most promising approach seems to be to use a raytracer to provide the loading inside the compartment in a very fast but reasonably accurate manner, accounting for multiple reflections[8].

2.3 Conclusion

In this section, we investigated the feasibility of using LS-DYNA to simulate accurately the propagation of an internal blast in a large domain (equivalent to the size of a typical compartment-type vessel). Several approaches were presented and demonstrated that there are many constraints that need to be addressed before getting accurate predictions. A full 3D CFD/ALE modeling of the loading, including multiple reflections, with a resolution sufficient to represent shock effects accurately everywhere in the compartment, is almost certainly unrealistic. However, alternative approaches were suggested.

[8] At this time, work was started to program the raytracer, but some validation has to be done and the coupling with LS-DYNA has not been implemented yet. This is part of future work that could be addressed in future CSC stemming from B-31[Peg et al. (2012)].

3 Damage and failure modeling

This section highlights the most important aspects to consider when modeling damage/failure of elements in a FE element model. First, we looked at the way LS-DYNA achieves erosion in its material models. Then, we present only three studies on the modeling of damage of bulkheads and decks as there was very limited amount of information available in the open literature on this subject. These studies could be very useful if this project is pursued.

3.1 Erosion/failure in LS-DYNA

According to Schwer (2009), one possible solution to include erosion in a finite element analysis is to follow these three steps:

1. Select an ad hoc erosion criterion
2. Select a critical value for the erosion criterion
3. Perform a mesh study: the results should be converging and the error due to discretization should be small enough.

Since the selection is ad hoc, the erosion criterion should be calibrated with experimental data or at least, a mesh refinement analysis should be performed on the model.

The most common criterion used in LS-DYNA is the effective plastic strain. Since the value for erosion in the element is the same in tension and in compression, it is not recommended to choose this type of criterion unless experimental data are available to validate the criterion. In Martec (2005) report for example, material properties were modified to include plasticity and failure strain.

In LS-DYNA when using the **mat_add_erosion* card, it is possible to define multiple independent criterion based on, for example, the maximum or minimum pressure, the maximum or minimum principal strain, the maximum shear strain, etc. It is also possible to include a GISSMO (Generalized Incremental Stress State dependant damage Model) damage accumulation model including softening and failure or the user may invoke an arbitrary number of damage initiation and evolution criteria [LS-DYNA Keyword User's Manual Version 971 volume I and II (2012)].

When damage or failure is included in a simulation, the mesh topology is an important aspect because, damage and failure are often initiating in the smallest elements of a mesh. Therefore, doing a mesh refinement study to establish the failure criterion on the compartment is required. A mesh as uniform as possible should be used when predicting erosion, otherwise the smallest elements should be modeled in the area where damage and failure seems probable. By changing the size of element at different locations, we might change the predicted results. Experimental data seems required to validate the failure model.

3.2 Studies on the modeling of damage of bulkheads and decks

Iwahashi et al. (1998) presented a comparative study of the local stresses developed at the intersection structure of longitudinal stiffeners and a transverse bulkhead between eight shell element models and two solid models. The author recommended using 3D solid elements to get a precise prediction of local stresses at weld connections. If shell elements were to be used, a reliable and practical procedure has to be developed to allow a proper prediction of the local stresses.

Raymond (2001) presented in his master of engineering the tools needed for the formation of optimised X-80 steel blast tolerant transverse bulkheads. This thesis included all the procedure followed to get to this optimisation. Amongst other things, the definition of design criteria from the worst case operational requirements, high strain rate data and analysis to determine the constants and constitutive models to be used in the FE model, development and evaluation of a FE modelling technique were presented. The thesis presented some factors related to the design constraints (stress waves and strain rates and prediction of rupture) and an investigation on bulkhead components (joint and stiffener structures).

Tyler-Stree and Luyten (2009) have used the dedicated element methodology (DEM) developed by Dillingh (2003) specifically to predict ductile failure of welded bulkhead-deck connections due to an internal blast. The authors reported that due to the size of the structure involved (ship), it was not possible to use a fine element mesh to model the structure. Therefore, to get a reasonable amount of energy dissipation and a more realistic elongation before failure, the failure criteria should be adjusted to larger element size (i.e. in the order of typical shell meshes used for ship analyses).

3.3 Conclusion

Due to time constraint, it was not possible to perform FE analysis including damage and failure to evaluate the damage on structures (such as bulkheads and deck) in the compartment-type vessel. However, in the future, a method should be developed to predict the damage and failure in large scale model.

This method could be to use an existing damage model and failure criterion available in LS-DYNA (ex. the Johnson-Cook model with damage, the GISSMO (Generalized Incremental Stress State dependant damage MOdel) in the **mat_add_erosion* card, etc.). Or it could be use a particular method (see the ones presented in section 3.2) or develop a new one. In either case, a study on the size of the mesh will be needed to predict damage/failure in the compartment. Experimental data should also be used to validate the model.

Finally, one alternative to predict damage on the compartment would be to look at the stresses developed in the structures instead of eroding elements in the structure. This method would be simpler and would not require the development and validation of a damage/failure model.

4 General Conclusion and Recommandations

This document presented an investigation on the feasibility of using LS-DYNA to perform the finite element structural analysis to study the structural damage of a typical compartment-type vessel. The work was divided in two main parts: various studies were conducted to generate and propagate a free air blast and a discussion on damage and failure models was initiated.

In the first part of the work, four studies were presented to generate and propagate a free air blast. In each study, a large domain that could contain a typical compartment was meshed.

The first and second studies, demonstrated that an ALE model with a rectangular mesh with element size of 200 mm, 100 mm, 75 mm and 50 mm could not predict accurately the maximum incident pressure and impulse at distances of 1.5 m, 2.0 m and 3.0 m from the center of detonation. In order to capture accurate shock pressure and impulse, a rectangular mesh with element size in the order of 1 to 10 mm would probably be required.

The third study presented the **load_blast_enhanced* (LBE) approach combined to a multi-material arbitrary lagrangian eulerian (ALE) model in LS-DYNA. The study showed that we can use the LBE-ALE technique with element size of 100 mm and get representative maximum incident pressure and impulse on the first layer of elements of the ALE domain. However, only a direct loading has to be considered (everywhere where there are no ALE elements, reflections from walls, floor or ceiling are not considered). Also, for this work, since CONWEP impulse was only valid for target distances beyond 7.57 charge radii, threat close to the walls, ceiling or floor cannot be simulate using the LBE-ALE approach.

In the fourth study, a spherical mesh was used to propagate a free air blast detonated in the center of the compartment. The simulation demonstrated that a spherical mesh with 3,222,400 elements provided maximum incident pressures and impulse closer to the CONWEP predictions compared to a rectangular mesh with 3,517,344 elements. Another advantage of the spherical mesh compared to the rectangular mesh was that there is no directional dependence of the mesh. However, the loading resulting from multiple reflections would not be accurate. Also, this model cannot be used to simulate a detonation everywhere in the box as it would require increasing the sphere radius to still enclose the entire compartment when moving the spherical mesh and consequently, it would increase the number of elements.

Other methods could have been tested, however, due to the short time given to realise this work, it was not possible to investigate all of them. Considering the limitations of the different approaches to simulate an internal blast it is suggested to continue the development and validation of the raytracer approach.

In the second part of the work, the most important aspects to consider when modeling damage/failure of elements in a FE (finite element) model were highlighted. It was suggested to develop a method to predict the damage and failure in large scale model.

This method could be to use an existing damage model and failure criterion available in LS-DYNA (ex. the Johnson-Cook model with damage, the GISSMO (Generalized Incremental Stress State dependant damage Model) in the**mat_add_erosion* card, etc. Or it could be use a particular

method (see the ones presented in section 3.2) or develop a new one. In either case, a study on the size of the mesh will be needed to predict damage/failure in the compartment. Experimental data should also be used to validate the model.

Finally, the last alternative suggested to predict damage on the compartment was to look at the stresses developed in the structures instead of eroding elements in the structure. This method would be simpler and would not require the development and validation of a damage/failure model.

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Annex A Range of Applicability of CONWEP

Schwer (2010-A) presented a comparison between the pressure and impulse of a TNT free air burst predicted by CONWEP and given by Swizdak (1975) for 4.5 kg and 454.5 kg charges. The comparisons between them showed that the maximum incident pressures agreed quite well; however, CONWEP overpredicted the impulses at close range.

In his paper, Schwer (2010-A) explained how Kingery and Bulmash (1984) parameterized a collection of experimental data using TNT Equivalence of different explosives and cube root scaling of range, impulse and time with explosive weight combined with the Friedlander equation into a form that can be used by CONWEP. Kingery and Bulmash (1984) provided the range of applicability (in charge radii) for the positive phase duration for a spherical free air: 2.7 to 750 charge radii. Therefore, usually the minimum number of applicability used is 3 times the charge radii when using CONWEP.

Schwer (2010-A) also gave the range of applicability in terms of scaled distance (Z) by extracting data from Swizdak report. The scaled distance given was Z_1=0.404 to 28.18 kg/m$^{1/3}$ for 4.5 kg charge and Z_2=0.404 to 26.18 kg/m$^{1/3}$ for 454.5 kg charge. It is possible to transform these scaled distances in terms of charge radii. The scaled distance, comes from the cube root scaling method and is given by:

$$Z = \frac{R}{W^{1/3}} \tag{1}$$

where R is the range from the spherical charge (m), W is the mass of the charge (kg). For 4.5 kg, using equation (1), the R_1 (range from the spherical charge) obtained is 0.667 m and for 454.5 kg, the R_2 obtained is 3.106 m. The spherical charge radius r is given by equation (2):

$$r_{TNTcharge} = \left(\frac{3W}{4\pi\rho_{TNT}} \right)^{1/3} \tag{2}$$

Where ρ is the density of TNT and equals 1570 kg/m^3 [Kingery and Bulmash (1985)] and W is the mass of TNT (kg). For 4.5 kg, r_1=0.0881 m and for 454.5 kg, r_2=0.4104 m.

Finally, the charge radii is given by R_1/r_1 = 7.57 and R_2/r_2 = 7.57.

Using the scaled distance, the charge radii was calculated to be 7.57 for a 100 kg TNT charge. Therefore, since according to Schwer (2010-A), the maximum incident pressures agreed quite well for the range of distances given; a charge radii of 3 can be used for comparison with CONWEP's predictions but since CONWEP overpredicted the impulses at the closest ranges, a charge radii of 7.57 (corresponding to 1.852 m for a 100 kg TNT charge) should be used in this work to compare the impulse data with CONWEP's predictions.

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Annex B Incident pressure versus time examples

This annex presents a comparison between the incident pressure histories obtained for a rectangular mesh at distances of 1.5 m, 2.0 m and 3.0 m from the center of detonation for three rectangular meshes with element sizes of 100 mm, 75 mm and 50 mm.

Figure C-1: Incident pressure for a rectangular mesh with element size of 100 mm at 1.5 m, 2.0 m and 3.0 m.

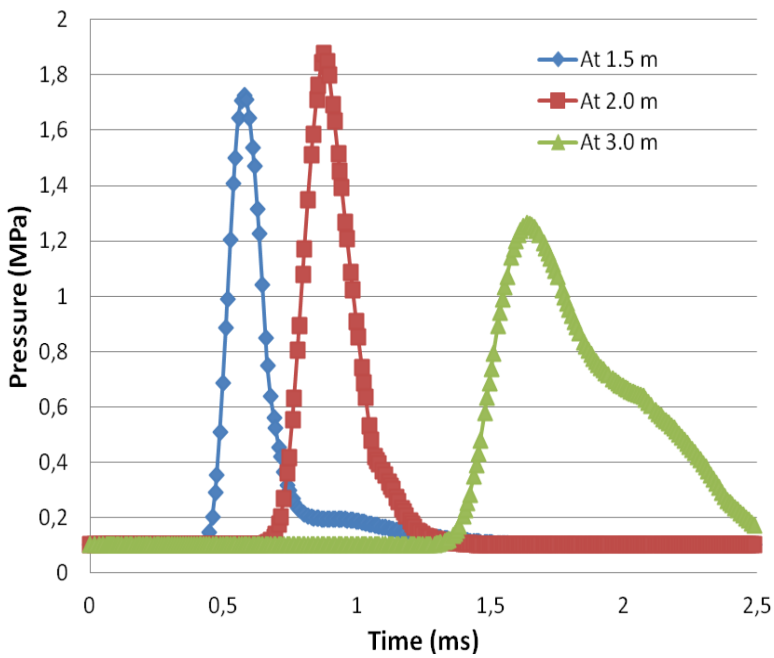


Figure C-2: Incident pressure for a rectangular mesh with element size of 75 mm at 1.5 m, 2.0 m and 3.0 m.

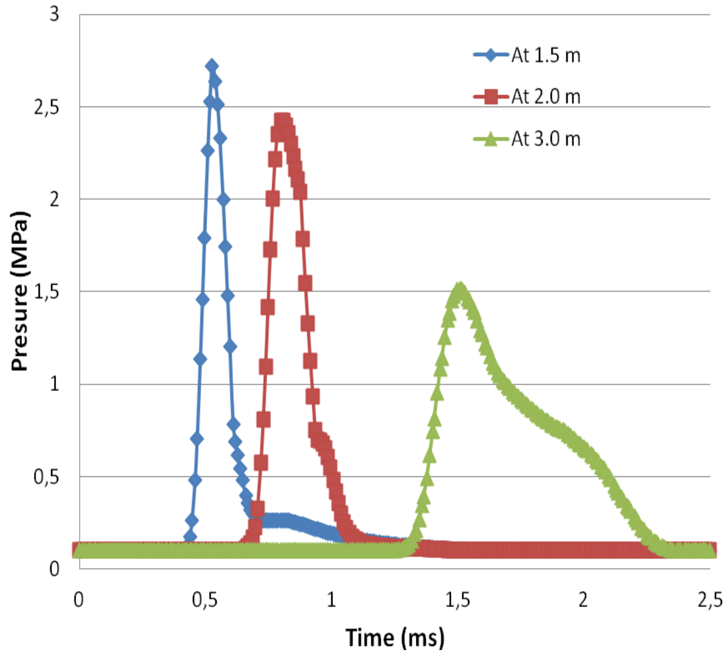
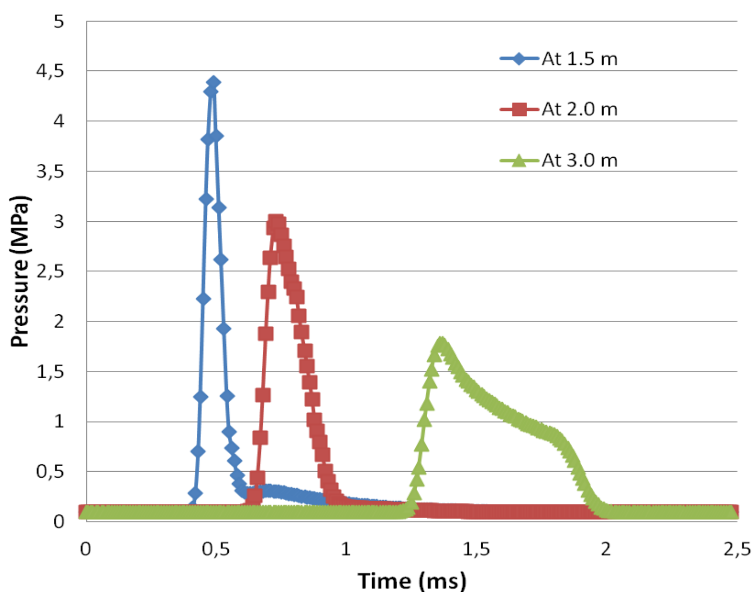


Figure C-3: Incident pressure for a rectangular mesh with element size of 50 mm at 1.5 m, 2.0 m and 3.0 m.



Annex C GVAM/INBLAST State of Work

This annex summarizes the state of work of GVAM/INBLAST from July 25th, 2012.

1. Stephane modified the INBLAST93 code to read GVAM INBLAST files. INBLAST93 includes a raytracer for shock modeling as well as the former QS pressure propagation algorithms. INBLAST93 had no response algorithms: (QS) failure pressures and minimum loading durations are user-input. These are normally predicted by the GVMFM1 pre-processor based on web, frame and stiffener spacing and resulting panel eigenfrequencies. Note that a lognormal damage algorithm is used to account for incontrollable variations in panel toughness and loading; the output rupture pressure is below the nominal one (conservative), although a true randomisation would be better (several INBLAST runs would be averaged)

2. RIPTASP was implemented in this for modeling rigid-plastic cross-stiffened panel response, as a replacement to the GVAM elastic response algorithms not trusted anymore. Note that RIPTAB beam algorithms are automatically used by RIPTASP if there is a single row of sub-panel cells. A limitation is that the code assumes a spatially uniform loading.

3. Another possibility would have been to use a Dynamic Load Factor in conjunction with a (probably clamped panel) rupture criterion as in Gass et al. (1988) (EXBLAST), but this did not work well in EXBLAST. Note that RIPTAB was already implemented as an alternative in EXBLAST.

4. (QS) Rupture for RIPTASP is to be based on the maximal strain in plastic parts of the sub-beams. The user will decide what level constitutes a rupture (2% is the onset of, 25% is quasi certain rupture). Note that GVAM INBLAST also lets the user decide the hole size in case of rupture.

5. The above works in quasi-static (QS) cases. For shocks, since RIPTAB assumes a spatially uniform loading, it was suggested using the above approach, but after defining an equivalent uniform pressure obtained by equating the associated moments M on a clamped edge associated to a spatially uniform and a distributed load, respectively. This implies a clumsy recalculation at each time step and all nodes. Another approach would be to use an impulse criterion as P. 27 of the above report or Chapter 3 of TM5-1300.

   The above formula is:

$$\mathrm{I\_C} = SD * h * A * B * \sqrt{rho * \frac{(1+N)(1-2N)}{E(1-N)}} \tag{3}$$

   Where I_C=critical impulse = ∫(P(x,y,t) dt dx dy) of positive pressure history over whole plate (N•s)

SD = Dynamic yield strength of material (110% of static one for steel following old TM5-855 9-2) (Pa)
h = plate thickness (m)
A, B = in-plate dimensions (m)
rho = plate density (kg/m^3)
N = Poisson ratio
E = Young's modulus (Pa)

This is simply based on the usual shock propagation formula by putting S = SD. S is given by the actual stress (Pa):

$$S = rho * C * V \tag{4}$$

V is the plate material velocity (here averaged in space coordinates) (m/s)

C is the in-plate shock velocity (m/s) given by:

$$\frac{1}{c^2} = rho * \frac{(1+N)(1-2N)}{E(1-N)} \tag{5}$$

6. The above approach applies obviously to single shocks only. If a reflected shock impinges the panel before rebound (if any) this will not work. The report suggests a (n obscure) method for dealing with this situation. Note that even if the panel has time to rebound before arrival of a reflected shock, it may nevertheless be deformed permanently, which may affect the yield pressure, thus affecting the effect of the second shock, another subtlety not accounted for by the above method.

7. Ideally, the raytracer should give a history load to the nodes in LS-DYNA. This could require some simplifications.

List of symbols and acronyms

A and B	In-plate dimensions (m)
ALE	Arbitrary Lagrangian Eulerian / Arbitraire lagrangienne eulérienne
C	In-plate shock velocity (m/s)
CFD	Computational Fluid Dynamics
CSC	Canadian Surface Combatant
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
E	Young's Modulus (Pa)
FE/EF	Finite Element/Éléments finis
GISSMO	Generalized Incremental Stress State dependant damage Model
I_C	Critical Impulse (N•s)
LBE	Load Blast Enhanced
N	Poisson's ratio
π	3.141592654
ρ	Density of explosive (kg/m^3)
r	Radius of the explosive charge (m)
R	Range from the spherical charge (m)
rho	Plate density (kg/m^3)
R&D	Research & Development
S	Actual Stress (Pa)
SD	Dynamic yield strength of material
V	Plate material velocity (m/s)
W	Mass of explosive (kg)
WEP	Weapons Effects and Protection
Z	Scaled distance ($kg/m^{1/3}$)

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Defence R&D Canada – Valcartier
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44</td><td>6b. NO. OF REFS (Total cited in document.)

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The objective of this document is to investigate the feasibility of using the LS-DYNA code to perform a finite element analysis to study the structural damage of a typical compartment-type vessel caused by an internal blast. The work is divided into two investigations: one considers the generation and propagation of the blast and the other investigation looks at the material-damage and failure models that could be used to predict the damage on the compartment structure.

The first investigation presents results and lessons learned from four studies. These studies simulated the blast propagation using the arbitrary lagrangian eulerian (ALE) approach in LS-DYNA. This investigation included parametric studies as well. Regardless of the work done, it was not possible to generate a finite element model, fine enough (and yet still manageable) to capture maximum incident pressure and impulse with a domain large enough to include the whole compartment. Alternative methods, such as the raytracer approach, were not part of this work but should be addressed in the future.

The second investigation discusses different issues regarding the use of damage and failure models in LS-DYNA. It is recommended to develop an ad hoc method to predict the damage and failure in large scale model. This method should include a material-damage model, a failure criterion, as well as a study on the mesh. Experimental data should also be used to validate the model.

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Compartment, ship, vessel, finite element analysis, blast, LS-DYNA, ALE, raytracer

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